Advances in Karst Science

Philippe Renard
Catherine Bertrand *Editors*

EuroKarst 2016, Neuchâtel

Advances in the Hydrogeology of Karst and Carbonate Reservoirs

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Advances in Karst Science

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Editors
Philippe Renard
Centre of Hydrogeology and Geothermics
University of Neuchâtel
Neuchâtel
Switzerland

Catherine Bertrand
Laboratoire Chrono Environnement
Université de Franche Comté
Besançon
France

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Preface

In 2014, the Universities of Malaga (Spain), Besançon (France), and Neuchâtel (Switzerland), jointly with the Spanish Geological Survey, decided to join their resources to launch the *Eurokarst* series of conferences. The first edition was held in Neuchâtel, Switzerland, in September 2016, and involved about 200 participants from more than 20 countries from all over Europe and the World. *Eurokarst* is the largest event on this theme in Europe.

The aim of the *Eurokarst* conference series is to continue promoting advances in the field of karst and carbonate reservoirs after more than 40 years of regular meetings that were held in these three universities.

These conferences were initiated in 1970 in Besançon by Pierre Chauve and dedicated to Eugène Fournier, one of the fathers of karst hydrology in France. At that time, the conference was named the *Colloque d'Hydrologie en Pays Calcaire*, and all the conferences were given in French. The second edition was in Besançon in 1976 and included 36 communications (groundwater circulation dynamics, tracers in karst, groundwater exploitation, underground engineering in limestone, etc.). In 1982, the conference moved to Neuchâtel. It was chaired by André Burger and included 27 presentations in French from French, Swiss, Belgium, Italian, and Slovak participants from universities and private companies or administrations (Burgeap, Service de Contrôle des Eaux de la Ville de Paris, Motor-Columbus AG, etc.). During the next 20 years, the *Colloque* continued to alternate between Neuchâtel and Besançon. In Besançon, Jacky Mania followed by Jacques Mudry took over the organization. In Switzerland, François Zwahlen, Imre Müller, Pierre-Yves Jeannin, and Nico Goldscheider ensured the continuation of the conference series with an incursion in La-Chaux-de-Fonds (Switzerland) in 1997. In the 1990s, the language of the conference became a mixture of French and English. In 2011, in Besançon, the name was changed to *H2Karst*. At that time, the event had reached a much larger audience with more than 200 participants including 27 nationalities and 126 presentations on a wide range of topics, including notably a large section on karst modeling.

In parallel with the joint French and Swiss conferences, the *International Symposiums on Karst* have been organized by the University of Malaga and the Spanish Geological Survey (IGME), under the coordination of Bartolomé Andreo, Juan José Durán, Francisco Carrasco, and coworkers. The first (1999) and second (2002) editions were organized in Nerja under the auspiciousness of the Nerja Cave Foundation. In 2006, 2010, and 2014, the symposium was held in Malaga city, and both national and international partnerships were involved. Again, the event was pretty large with around 110 presentations. It is during this last conference in Spain that was announced the merge of these events to create the *Eurokarst* conference series.

Today, the *Eurokarst* conference remains a platform where professionals, consultants, researchers, and students can meet to learn about new technologies and methods but also about new practical challenges encountered in applications.

While the original themes are still relevant—understanding how groundwater flows into carbonate and karstic formations, protecting and managing this resource against pollution and overexploitation—the approaches have evolved, and new problems and tools are emerging. In particular, the development of new analytical technologies enables hydrogeologists to monitor the behavior of karst at a much higher frequency and new parameters (natural tracers as well as emerging contaminants) can now been measured continuously in the field. This poses a challenge in terms of data treatment and analysis but also opens up a wide range of new possibilities for an improved understanding of these systems. These data are also challenging the conceptual and numerical models of karst by offering new ways to constrain or invalidate theories. An important trend is also the wider availability of massive computing resources and software allowing to construct three-dimensional models which were just impossible to build 20 years ago. How to use these models is still a topic of debate but also an important aspect to discuss during these conferences.

Among the various challenges posed for the twenty-first century, the development of renewable energy resources such as geothermics is a remarkable issue that karst hydrogeologists will have to tackle.

Last but not least, the world is facing global climate change. Understanding and forecasting the impact of this change requires on the one hand the systematic and long-term monitoring of physical and chemical parameters to record the changes and understand the processes, and on the other hand, it also requires the development of appropriate models able to describe and predict those phenomena.

To conclude, it is well known that karst aquifers are able to store abundant water resources that could become crucial under the growing pressure of global climate change and population increase in many places in the world. We are therefore convinced that continuing to conduct research on karstic systems remains critical and that events like *Eurokarst* are of prime importance.

In 2016, for its first edition, the *Eurokarst* conference included 164 communications covering a wide variety of topics in many fields related to karst. Among them, 35 are presented in this book. These articles provide an overview of recent progresses made in karst research. The articles are organized around six main topics:

- Geomorphology and geophysics;
- Geological control and speleogenesis;
- Hydrodynamics;
- Time series analysis and modeling;
- Karst aquifer management;
- Multidisciplinary regional studies.

As the organizers of the *Eurokarst* event and editors of this book, we are extremely thankful to a number of organizations and people who participated in the preparation of the event and without whom the book could not be published. First of all, we would like to thank the sponsors who contributed financially to support the conference:

- The French National Institute for Earth Sciences and Astronomy (CNRS-INSU);
- The Swiss National Science Foundation;
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- Springer Verlag AG.

The partner organizations were the following:

- The University of Franche-Comté, Besançon, France;
- The University of Malaga, Spain;
- The Spanish Geological Survey (IGME);
- The Swiss Institute of Speleology and Karstology (SISKA);
- The IAH Commission on Karst Hydrogeology;
- The International Association of Hydrogeology (IAH).

We want also to thank very warmly the members of the Scientific Committee of the conference and some additional reviewers (see list on following page) who have shared their expertise and knowledge with the authors in order to provide the best possible technical quality within the limited time frame available to publish the book. Finally, we want to thank Laurence Fischer who spent countless hours to polish the format of the papers as well as the persons in charge of the project for Springer: Jim LaMoreaux, Carlo Schneider, and Ramamoorthy Rajangam.

Philippe Renard
Catherine Bertrand
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July 2016

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Geomorphology and Geophysics

Shui Jing Po Shilin, Rock and Relief of Stone Forests on Cone Hills, Yunnan, China

Martin Knez, Hong Liu and Tadej Slabe

Abstract

Emerging gradually from the sediment and soil, the remarkable stone forests are a rich source of knowledge about the formation of karst surfaces. This is revealed by the details in the rock relief, subsoil rounded forms dominating the lower parts of the stone pillars, and sharp-edged rillen or fluting created by rainwater dominating the peaks. In between, all of the stages of gradual morphological transformation can be clearly seen. The shilin (Shilin County, Yunnan) pinnacles are developed on Permian limestones displaying a wide variety in lithology which, together with differing location (e.g., hillcrest v valley floor), creates their different characteristic shapes. The bedrock in the Shui Jing Po stone pillars is a micrite to microsparite limestone with (in some places) numerous recrystallised bioclasts, peloids, and intraclasts, that is very pure (high calcium carbonate content). The carbonate rock is uniform throughout the researched block of rock. Dolomitized areas, which are a very frequent and important characteristic of a majority of the neighboring stone forests, were not detected in the Shui Jing Po stone forest (■Figs. 1.1, 1.2 and 1.3). Lithomorphogenesis, rock and relief of stone pillars, shows typical characteristics of quick development of stone forest from subsoil karren on the top of cones and ridges between them and slower on the slopes beneath.

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Fig. 1.1 Shilin on the cone

1.1 Introduction

Stone forests, karst surfaces dissected into large rock pillars, are special and one of the most attractive karst features. A large proportion of rock forests develop with the long-term vertical dissection and lowering of the karst surface under the ground, sediments, or soil where the power of percolating water is strongest; later in their development, climate factors dominate the formation process. The dissolving of rock along predominantly vertical fissures and faults initially fosters the formation of cracks that can grow into wider corridors between individual blocks of unbroken rock. The pillars are distributed in networks of various densities and forms. The tops of pillars are pointed, blade-like, or flat, their walls are steep, vertical, or even overhanging, and their surface is dissected into rock relief that reveals the manner of their formation and development. Pillars measuring only a few meters in height are called stone teeth. The formation of stone forests and pillars is decisively influenced by local geological characteristics such as the stratification, fracturing, and composition of the rock (Grimes 2009; Knez and Slabe 2013; Hantoon 1997; Salomon 2009; Song and Liu 1992).

In southern China, stone forests occupy areas in size from tens to hundreds of square kilometers. One of the most remarkable examples are the stone forests—shilin—in the Shilin area of the Yunnan province. Here the stone forests tower 50 m high. The carbonate rock where karren first developed was covered by thick layers of sediment that had a decisive impact on the formation and shape of the stone forest. Three types of stone forest are distinguished based on their location: those in valley systems and valleys, those on peaks, and those on slopes. The identification of the formation of different carbonate rocks at different development stages and under specific regional conditions is one of the foundations for understanding the formation of karst and its development. This was further proven by the studies in Shilin (Chen et al. 1983, 1998; Ford et al. 1996, 1997; Knez 1998; Slabe 1998; Knez et al. 2011, 2012; Knez and Slabe 2001a, b, 2002, 2006a, 2007a, 2009, 2013; Kranjc and Liu 2001; Maire et al. 1991; Song 1986; Song and Liu 1992; Song and Wang 1997; Sweeting 1995; Zhang et al. 1997; Yu and Yang 1997; Yuan 1991, 1997).

The extent, distinctiveness, and occurrence of the stone forests are reflected in the traditional names for this karst surface feature in other parts of the world. In Madagascar, they are called *tsingy*; in the Philippines, *assegai*. Among exceptional and famous stone forests are the Mulu stone forests in Sarawak that tower up to 100 m high and Mount Kaijende in Papua New Guinea. Stone forests are also found in Cameroon, Congo (Kouilou), Kenya and Tanzania, Brazil (Bom Jesus da Lapa), Thailand (Ta Khli), northern Australia (Gregory Karst), and Spain (El Torcal), and there are unique stone forests in calcareous aeolianites in Namburg National Park in Western Australia (Day and Waltham 2009; Ford and Williams 2007; Mangin 1997; Narbona 1989; Salomon 2009; Williams 2009).

Established lithogeomorphological methods were used to link detailed rock studies (limestones, dolomitized limestones) with the study of surface formation. Rock relief is often important trace of shaping and development of karst features. In the rock relief of the Shilin stone pillars, it is possible to trace the development of subsoil karren into a stone forest whose denuded sections have been reshaped mostly by rainwater and trick-

◘ **Fig. 1.2** Pillars on the *top* and stone teeth on the *lower part* of the slope

ling water. Special attention was devoted to the impact of geomorphological characteristics on the formation of stone forests that developed on the peaks and slopes of rounded hills. Micrometric studies of the dissolving of carbonate rock on the surface in the Shilin area led to the preliminary finding that the surface is lowering at the rate of around 35 m per million years and correspondingly faster along mostly vertical fissures and crushed zones.

1.2 Position and Shape of Stone Forest

The largest groups of the tallest stone pillars developed on wide rounded peaks (◘Figs. 1.1, 1.2 and 1.3) and on the ridges between them, i.e., on the tops of hills dissected by an extensive stone forest. The stone pillars often vary in height with individual pillars standing out distinctly. Mostly individual stone pillars are also found lower on the slopes. The latter are shorter as a rule (◘Fig. 1.4). Only individual narrow belts and rarely larger areas of stone forest, which as a rule are taller, are densely packed. Narrower stone pillars dominate in all parts of the stone forest, and only individual larger rock masses are found between them. This form was dictated by a relatively dense network of vertical fissures along which subsoil cracks had already developed.

The taller pillars reach 10 m (◘Fig. 1.5) in height but most are lower, and only the tallest, which are rare, are even higher. The beds of rock differ in thickness, and the tops of stone pillars that formed on thin beds are distinctly dissected and jagged. The caps of individual pillars stand on narrow bases. They are from a more durable rock bed and are consequently wider. There are many stone teeth (◘Fig. 1.6) up to 2 m high on the slopes.

1.3 Geological Characteristics

1.3.1 Macroscopic Description

The collection of rock samples began in the area of stone teeth at the bottom between two elevations where the rock barely outcrops on the surface and ended at the top of the elevation where the stone pillars stand up to 15 m tall. Around 80 m of the upper section of the elevation was studied in detail.

The rock is thickly bedded, the thickness of beds ranges between one and several meters, and 2- to 3-m-thick beds dominate. The dip of the beds from the foot to the top varies slightly with the prevalent dip between 5° in the lower part of the geological profile and 13° at the top of the elevation. The direction of the dip of the beds is between 300° and 320°. The rock is broken into larger blocks. Fissures and faults can be traced in all directions. In the lower part of the profile, fissures in the directions 330°–150°, 320°–140°, 300°–120°, and 315°–135° dominate, and in the upper, 320°–140° and

Fig. 1.3 Rock relief of the stone pillar: **a** rain flutes and rain channels, **b** channel from top, **c** funnel-like notch, **d** channel from bedding-plane cavities, **e** subsoil channel, **f** wall subsoil channel, **g** subsoil scallops, **h** subsoil half-bell, and **i** subsoil cavity

340°–160°. The color of the rock is gray, dominated by N7, 5B 7/1, and N6 (Goddard et al. 1970). Seventeen rock samples were taken from the profile for microscopic examination.

1.3.2 Microscopic Description

A total of 26 microscopic preparations were made from 17 samples and studied in transmitted light. Prior to the microscopic examination, half of each sample was dyed in alizarin red dye (1,2-dihydroxyanthraquinone, known also as Mordant Red 11, Evamy and Sherman 1962). Combining the observations with the results of the complexometric titration analysis, we were able to determine the properties of the rock.

The rock is very monotonous and homogeneous throughout the entire geological profile. Biomicrite to biomicrosparite limestone (wackestone to grainstone) dominates (Fig. 1.7). The rock from the lower section of the profile was classified as packstone to grainstone. Grains in the rock touch one another; the cement is micrite to microsparite. The rock from the upper section is wackestone to packstone. Here, in places, the grains in the rock touch one another, but elsewhere not; the cement is micrite. The carbonate grains, both allochems and cement, are very similar in size throughout the profile. Carbonate grains between 40 and 130 μm in diameter dominate in more than 90 % of the profile. Only individual beds contain up to 10 % fossil remains and intraclasts between 0.5 and 2 mm in diameter. In the upper section of the profile, the rock is somewhat tec-

Fig. 1.4 Shorter pillars on the slopes

Fig. 1.5 Taller pillars on the *top*

tonically fractured. Numerous calcite veins between 40 and 200 μm thick were found there. The occurrence of rock fissuring coincides with the occurrence of micrite cement. Numerous heavily recrystallized and micritized whole and fragmented bioclasts were found in all the beds. Whole foraminifers or their fragments dominate the fossil remains. Only exceptionally are mollusk fragments found, and in places, whole corals. Peloids are found in all the samples, in some places more frequently and other places less so. The upper section of the profile also contains numerous intraclasts.

The lower section of the profile is composed of biomicrosparite limestone (packstone to grainstone). Comprising more than 90 % in most cases, bioclasts strongly dominate in the rock. Most frequently, we find various foraminifers, ostracods, and individual coral and mollusk fragments. Pellets are frequently found in some samples from the lower section of the profile. Intraclast fragments occur only rarely. All the allochems, which are frequently micritized to such a degree that their basic structure is no longer recognizable, occupy more than 95 % of the volume. Clast sorting is not evident. The cement is micrite to microsparite. Due to intensive micritization, the clasts often transform smoothly into sparite and microsparite cement. Fenestrae up to 1.5 mm occasionally occur filled with mosaic sparite calcite. Fenestrae up to 3.5 mm in diameter occur only rarely. In some larger sparite areas, it is not completely clear whether they represent fenestral filling or an extension of widened fissures filled with sparite. Umbrella porosity is rare. There are no signs of compaction or stylolites in

Fig. 1.6 Recently uncovered subsoil shaped stone teeth

the rock. Also, no secondary porosity is evident. At the very bottom of the profile, only one sample displayed dolomitization. The dolomitized section, possibly an intraclast, is filled by up to 90-μm-large dolomite sparite crystals. Only exceptionally are calcite veins up to 45 μm filled with sparry calcite observed. No slips are observed along them.

An important change in the rock of the upper section of the profile is the occurrence of micrite cement and numerous fine calcite veins. The rock comprising the top of the elevation is biomicrite limestone (wackestone to packstone). Among the bioclasts whose content is between 90 and 95 %, uniserial and biserial foraminifers, ostracods, mollusk fragments, and occasionally partial or whole corals dominate. Numerous intraclasts of irregular shape with diameters between 0.2 and 2 mm are found among the non-bioclastic grains. All the carbonate grains are heavily micritized and have lost internal structure, and therefore, it is mostly impossible to distinguish fecal pellets from other grains. Micritized grains transform smoothly into micrite cement, so it is frequently difficult to establish the border between carbonate grains and cement. Grains or fine crystals of pure calcite occur relatively rarely. In the upper section of the profile, we observed signs of compaction and sorting. The longer axis of the grains is oriented parallel to the bedding. Fine drusy sparite with no internal structure fills the inner parts of bioclasts (ostracods and large foraminifers). Calcite veins of at least two generations are frequently found, in most cases oriented across the bedding. The calcite veins are between 40 and 80 μm wide. The slips along several generations of calcite veins are small, in most cases not exceeding 40 μm. Fenestrae filled with mosaic drusy sparite and secondary porosity were not observed in the upper section of the profile.

1.3.3 Complexometric Analyses

The dissolving method (Engelhardt et al. 1964) was applied in 17 complexometric analyses of 17 rock samples (Table 1.1). It was established that all samples from the profile reach 100 % total carbonate. All the samples in the lower section of the profile exceed 98.5 % calcite, with two exceeding 99 %. The amount of dolomite is below 1.5 % everywhere. The samples in the upper section of the profile exceed 97.2 % calcite, with two exceeding 99.4 %. In one case the amount of dolomite reaches 3.5 %. In most cases however, it is below 2 %. The average amount of calcite for all samples is almost 98.5 %. The average amount of dolomite for all samples is just above 1.5 %.

1.3.4 Impact on Karstification

Despite the sometimes macroscopically slightly different rock where we took the samples, it turned out that the

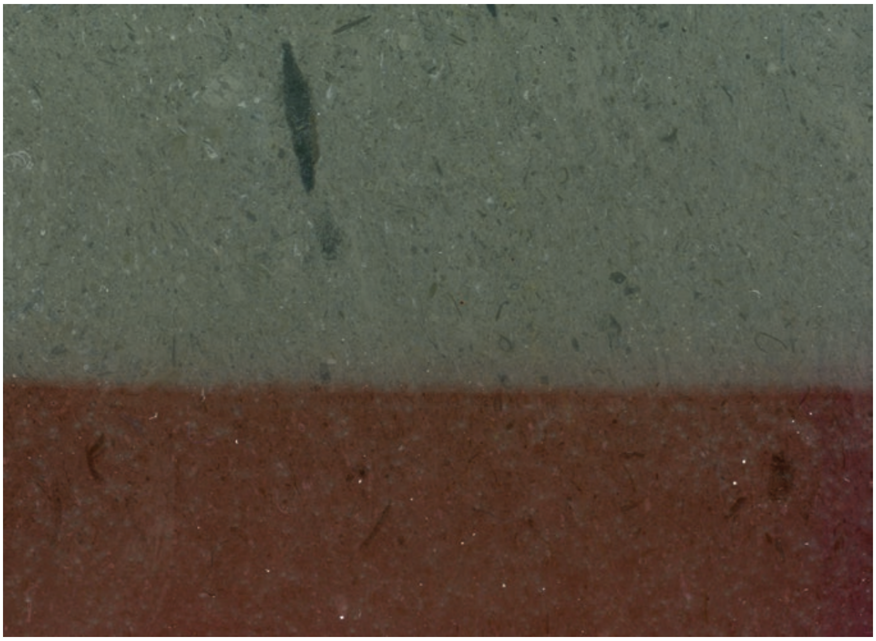


Fig. 1.7 Typical limestone (thin section)

Table 1.1 Complexometric analyses

Rock sample	CaO (%)	MgO (%)	Calcite (%)	Dolomite (%)	Total carbonate (%)	CaO/MgO	Insoluble residue (%)
1	58.26	0.20	99.08	0.92	100	291.30	0
2	58.49	0.28	98.71	1.29	100	208.89	0
3	58.37	0.28	98.71	1.29	100	208.46	0
4	58.32	0.55	99.45	0.55	100	106.04	0
5	58.60	0.24	98.90	1.10	100	244.17	0
6	58.49	0.32	98.53	1.47	100	182.78	0
7	58.43	0.24	98.90	1.10	100	243.46	0
8	57.76	0.12	99.45	0.55	100	481.33	0
9	58.15	0.32	98.53	1.47	100	181.72	0
10	58.26	0.28	98.71	1.29	100	208.07	0
11	58.21	0.40	98.16	1.84	100	145.53	0
12	57.76	0.76	96.50	3.50	100	76.00	0
13	57.59	0.56	97.42	2.58	100	102.84	0
14	58.26	0.40	98.16	1.84	100	145.65	0
15	57.65	0.60	97.23	2.77	100	96.08	0
16	58.15	0.48	97.79	2.21	100	121.15	0
17	58.65	0.20	99.45	0.55	100	293.25	0

composition of the rock is very even, homogeneous, and uniform throughout the entire thickness of the studied geological column. Through the macroscopic and microscopic studies, this unchanging composition confirmed that the karstification of the beds comprising the studied profile took place at the same rate.

1.4 Rock Relief

At the tops of rounded hills, the stone pillars are relatively thoroughly transformed by rainwater. The relief at the top of the stone pillars has been distinctly transformed or has developed into the forms that occur due to rainwater and water trickling down the walls. Their lower sections, however, still have preserved subsoil rock forms, subsoil cavities in particular. The rock relief is impossible to see on densely fractured rock, which on a large surface is dissected by numerous notches and is not infrequently densely perforated. The tops of the stone pillars that formed on such rock are especially diversely dissected.

1.4.1 Subsoil Rock Relief

Gently sloping subsoil channels (Slabe and Liu 2009) developed on the bottom of the crevices between stone pillars and on the lower rock below individual stone pillars. At the foot of the stone pillars below wall channels (◘Fig. 1.8a), they are up to 1 m deep and half a meter wide. Relatively shallow but clearly visible vertical subsoil channels measuring up to 1 m in diameter are found on the lower sections of the walls of the stone pillars; however, on the upper sections they have been fundamentally transformed. The individual largest channels, more than 1 m in diameter, have been utterly transformed by rainwater and creeping water and indent the wall from the top to the funnel-like notch in the lower section. There are vertical ridges with wider tops between the largest wall channels.

The channels are often wider at the contact with subsoil cavities.

Overhanging walls in places display shallow pockets of larger diameters that could be subsoil scallops transformed by creeping water.

Subsoil funnel-like notches are most distinct on the sections of pillars just above the ground (◘Fig. 1.8b) and on stone teeth. These are the mouths of vertical subsoil channels as a rule. The largest funnel-like notches reach several meters in diameter, and after the long-term dissection of carbonate rock from a large rock mass, groups of stone columns occur in places on the walls of funnel-like notches. They are an important legacy where the denuded rock has been carved by rainwater on the upper section of the pillars.

The most distinct subsoil wall notches (◘Fig. 1.8c) are found up to 1 m above the ground. They are usually fairly shallow, which indicates a relatively rapid lowering of the level of sediment and soil surrounding the rock. Traces of wall notches, which are most often dome-like in shape and testify to former somewhat long-term levels of soil and sediment, are also found higher up on the pillars (◘Fig. 1.8d). They also dissect the walls of subsoil funnel-like notches and half-bells. The notches found at the foot of the stone teeth on the ridge between the rounded peaks appear to be somewhat larger than those on the slope. Could this be due to the current more rapid lowering of the level of soil and sediment surrounding and covering the rock?

Subsoil half-bells (◘Fig. 1.3h) are found below subsoil channels and funnel-like notches and especially below more distinct vertical fissures in particular. They developed at points where a more distinct stream of consolidated water flowed to the level of the soil surrounding the rock.

Larger gently sloping surfaces also have large subsoil channels that form when only their bottoms are covered by soil (◘Fig. 1.8e, f). The deepest, up to 1 m deep and several meters long, have cross-sections in the shape of an inverted omega letter and semicircular bottoms. Their subsoil formation is only clearly visible from their floors since their walls have been transformed by rainwater. The walls still have preserved subsoil notches, the traces of former long-term soil levels. Wider gently sloping tops are often dissected by a relatively dense network of medium-sized subsoil channels that could have formed from interbed anastomoses when an upper bed of rock was removed. Interbed anastomoses grew from small tubes to larger, up to 1 dm large cavities cut into the bed of rock below the bedding plane. On steeper parts of the rock that was covered by soil, channels with 1-cm cross-sections run side by side. Subsoil cups (◘Fig. 1.8g) have one to few decimeter cross-sections. Denuded subsoil cups transform into solution pans. They are often found at the bottom of funnel-like notches, and denuded subsoil cups quickly become merged with the channels below them. Along more distinct fissures, cups of various sizes are arranged in strings. A subsoil cup that formed at the edge of a wider gently sloping top is open on the outer side and clearly shows the outline of a funnel-like notch. These forms also include those whose bottoms are overgrown by moss.

Subsoil cavities are among the most frequently found and distinct forms. Horizontal ones developed along bedding planes and fissures (◘Fig. 1.9a, b) and vertical ones along fissures (◘Fig. 1.9c, d). In most cases, they have

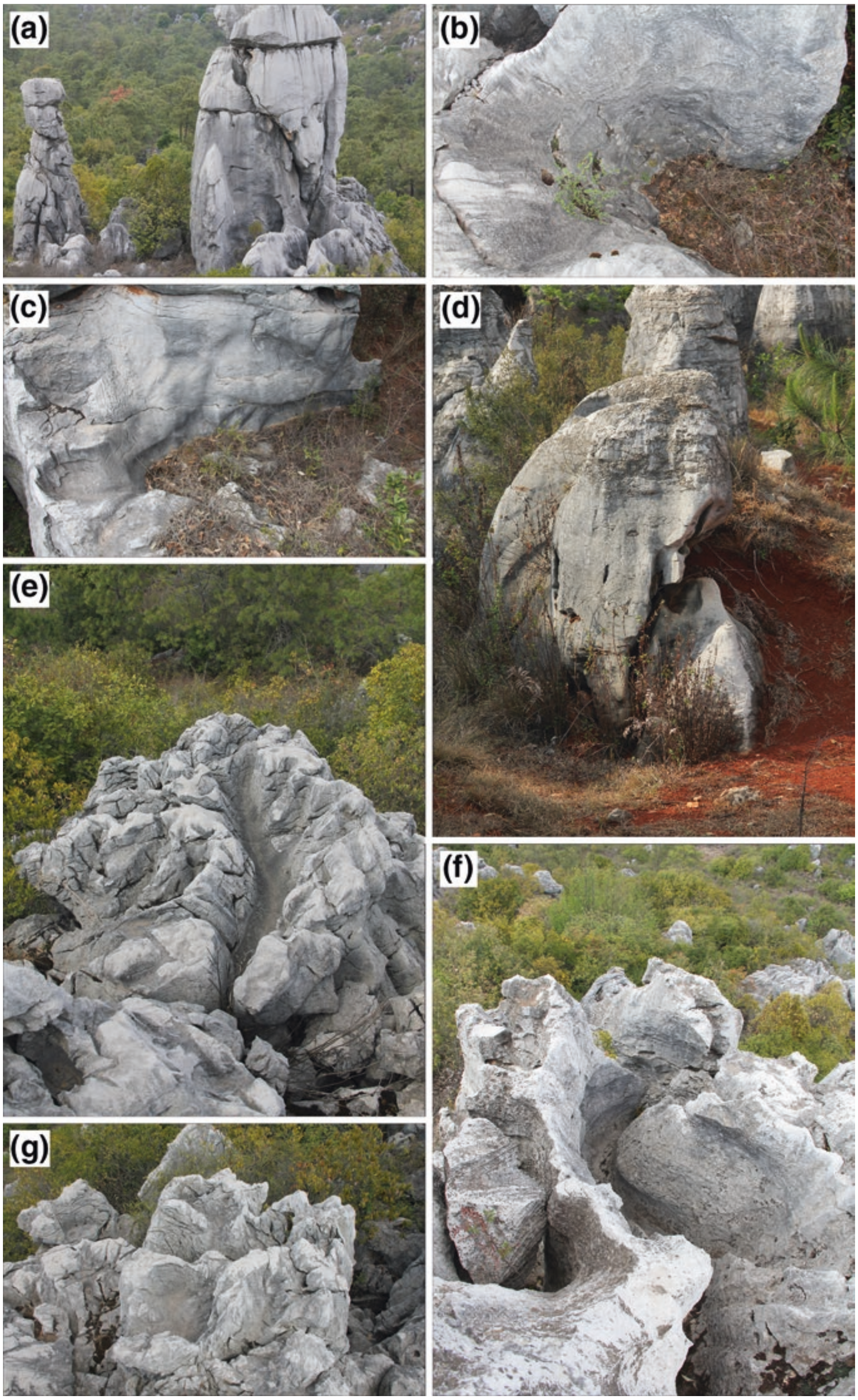
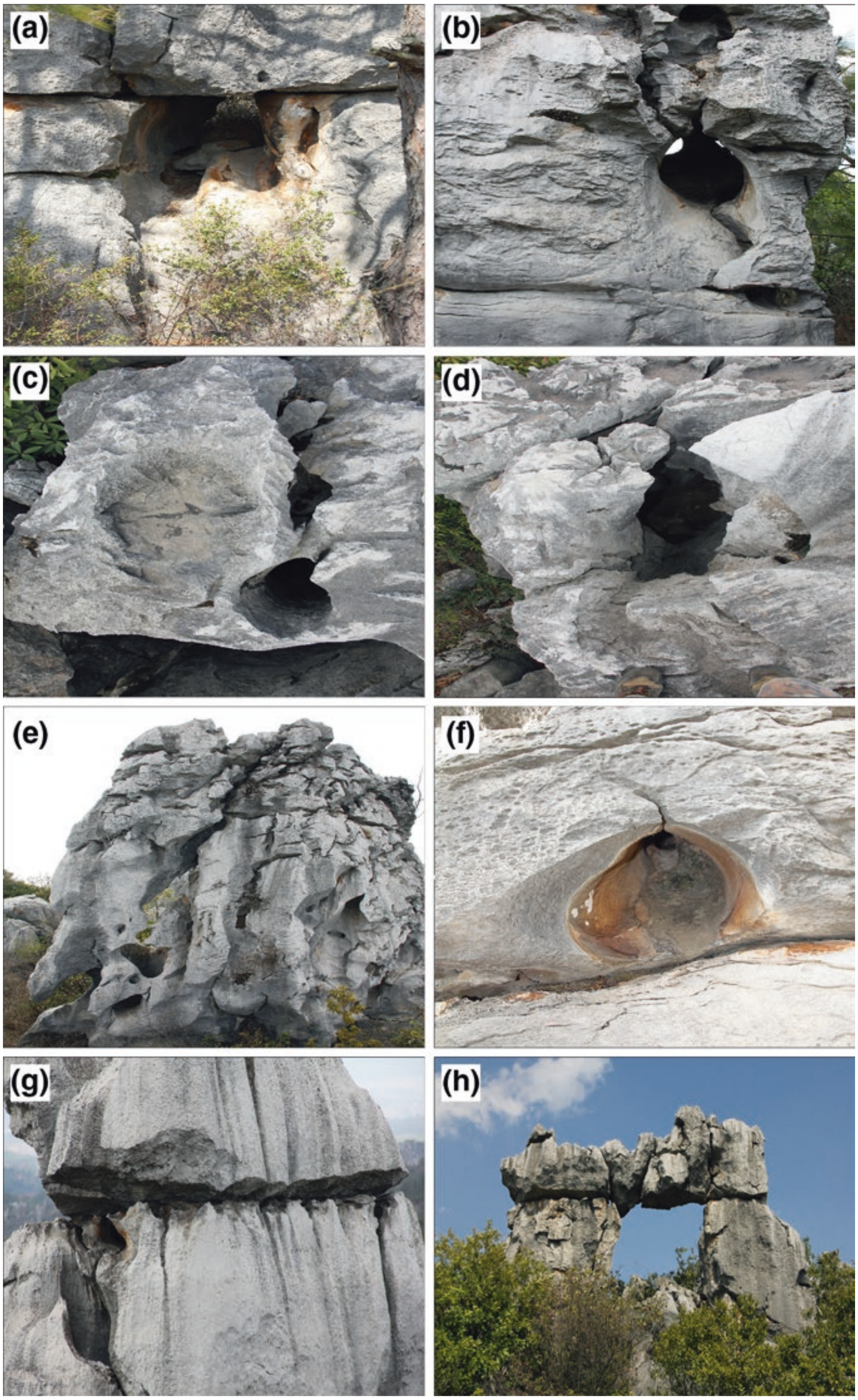


Fig. 1.8 Subsoil rock forms: **a** subsoil channel, **b** subsoil funnel-like notch, **c** subsoil wall notch, **d** wall notches, **e**, **f** subsoil channels, and **g** subsoil cups

circular or elliptical cross-sections, and some are further hollowed out in their deeper parts. They formed when the rock was under soil and sediment. Some were later transformed under the sediment that partly filled them. Dense networks of subsoil cavities formed on distinctly fissured rock (Fig. 1.9e). That some have merged is clear from their cross-sections. The mouths of some subsoil cavities, both horizontal and vertical, are distinctly widened. In places, bell-like pockets (Fig. 1.9f), the traces of vertically flowing water and vertical subsoil channels,



◘ **Fig. 1.9** Subsoil cavities: **a** cavity along bedding plane, **b** cavity along fissure and bedding plane, **c** vertical cavity along fissure, **d** vertical cavity along fissure, **e** network of cavities, **f** half-bell, **g** cavities along bedding plane, and **h** stone bridge

formed below vertical subsoil cavities. Interbed anastomoses (◘Fig. 1.9g) developed along distinct bedding planes. Small cavities are 1 cm in diameter. After the lowering of the level of sediment and soil that surrounded the rock, they are transformed by trickling water that in places brings soil from the surface and deposits it on the bottoms of the cavities, deepening them in the process. Some cavities that formed at the intersection of more distinct bedding planes and vertical fissures grew into subsoil caves with 1-m diameters. The bottoms of these are usually deepened under the soil. Many are transformed into stone bridges, one quite large (◘Fig. 1.9h).

In most cases, only the tops of the stone teeth (◘Fig. 1.8d) on the slope are dissected by rain flutes. Lower down, they are 1 or 2 m high, sometimes higher, and even their tops are smooth, dissected by subsoil rock forms and even subsoil-undercut, which indicates a relative rapid denudation of the rock in the last period. Shallow subsoil notches dissect their walls, and funnel-like notches dissect their tops. Composite stone teeth are also easily seen where a steep fissure crosses the rock mass in a large arc and small teeth develop below larger overhanging teeth (◘Fig. 1.8d).

1.4.2 Rock Forms Carved by Rainwater and Water Creeping Down Walls

Sections of the stone forest on rounded peaks and the ridges between them are quite distinctly transformed by rainwater that reaches the rock directly or creeps down it.

Rain flutes (◘Fig. 1.10a) cover the majority of the tops of the stone pillars with the exception of those tops that developed on densely fractured rock, and parts of the walls that are directly exposed to rain (◘Fig. 1.10b). On wider tops, networks of channels develop between ridges where flutes are found. Water flows down these channels to the edge and as a rule through a funnel-like notch into a wall channel (◘Fig. 1.10c). The funnel-like notch, which can be of subsoil origin, deepens, and its walls become covered by rain flutes (◘Fig. 1.10d). Funnel-like notches also dissect some ridges (◘Fig. 1.10e). The walls of stone pillars whose rock beds have different compositions and degrees of fissuring have flutes occurring in belts. Of course, these belts only form on beds that protrude from the walls. On the top of the caps of stone pillars are conical peaks completely covered by flutes, while the overhanging wall below them is covered by rain scallops and the bottom of the overhanging cap by small ceiling pendants (◘Fig. 1.10d). Rain flutes are frequently found only on the tops of stone teeth located on the slopes. Rain pits are found on relatively rare more or less horizontal surfaces, most often on the tops of wide ridges. They also dissect flutes on gently sloping surfaces.

On the upper sections of walls below wider tops where water flows along channels to the edge, there are 1-dm channels (◘Fig. 1.10d, f) of various depths, some quite deep. In some shallow channels that begin at the edge and developed mostly from the direct impact of rain, there are flutes. There are rain scallops (◘Fig. 1.10g) on overhanging surfaces.

Solution pans usually develop from denuded subsoil cups (◘Fig. 1.8g) on wider, relatively flat tops or at the bottom of funnel-like notches. On fractured rocks, they have dissected, often angular shapes and jagged edges. Those that deepened enough to reach the bedding plane are distinctly wider along it, and their walls consequently overhang.

Water that percolates through vertical fissures transforms anastomoses (◘Fig. 1.10h) of subsoil origin, flows to the edge, carves a funnel-like notch, and runs downward through a channel on the wall. It hollows out the lower part of the cavity.

On walls not reached directly by rainwater, there are rain scallops (◘Fig. 1.10g), 1-cm cups connected in a network. On vertical and slightly inclined surfaces, they are shallow, arranged in places somewhat like scales, while on overhanging surfaces they are deeper with emphasized edges; on ceilings, pendants form. This is the consequence of sheets of water flowing evenly over rock inclined at different angles.

1.4.3 Subsoil Rock Forms Transformed by Rain and Creeping Water on Walls

Rock forms carved by rainwater and water creeping down walls develop on subsoil rock relief. The water transforms subsoil rock forms, and smaller forms carved by rainwater develop on larger subsoil forms (◘Fig. 1.11a).

Rainwater and creeping water transform subsoil wall channels and their often funnel-like mouths (◘Fig. 1.11b, c). The consolidated flow of water from the top accelerates the deepening process, and their semicircular cross-sections take the form of the letter V; the rainwater covers the ridges between them with rain flutes. Similar cross-sections are also acquired by subsoil channels on gently sloping surfaces that in places were covered by soil. In most cases, the original subsoil rock formation is visible only at their bottoms, while the V-shaped cross-sections and the flutes on their edges testify to a long-term transformation by rainwater (◘Fig. 1.11d). Denuded subsoil cups transform into solution pans (◘Fig. 1.11e) that gradually acquire flutes on their edges and walls; if they open, their bottoms become dissected by channels that collect water flowing from the flutes covering the higher parts of their interiors (◘Fig. 1.11f).

Denuded subsoil shafts are first marked by channels and scallops, the traces of water creeping vertically down the walls, and the mouths exposed to rain are dissected by rain flutes. The bottoms of gently sloping cavities are deepened by water percolating from the surface. Their cross-sections change from circular or elliptical to shapes with a larger part where gravity causes the water to flow downwards. The cavities of a network of subsoil anasto-

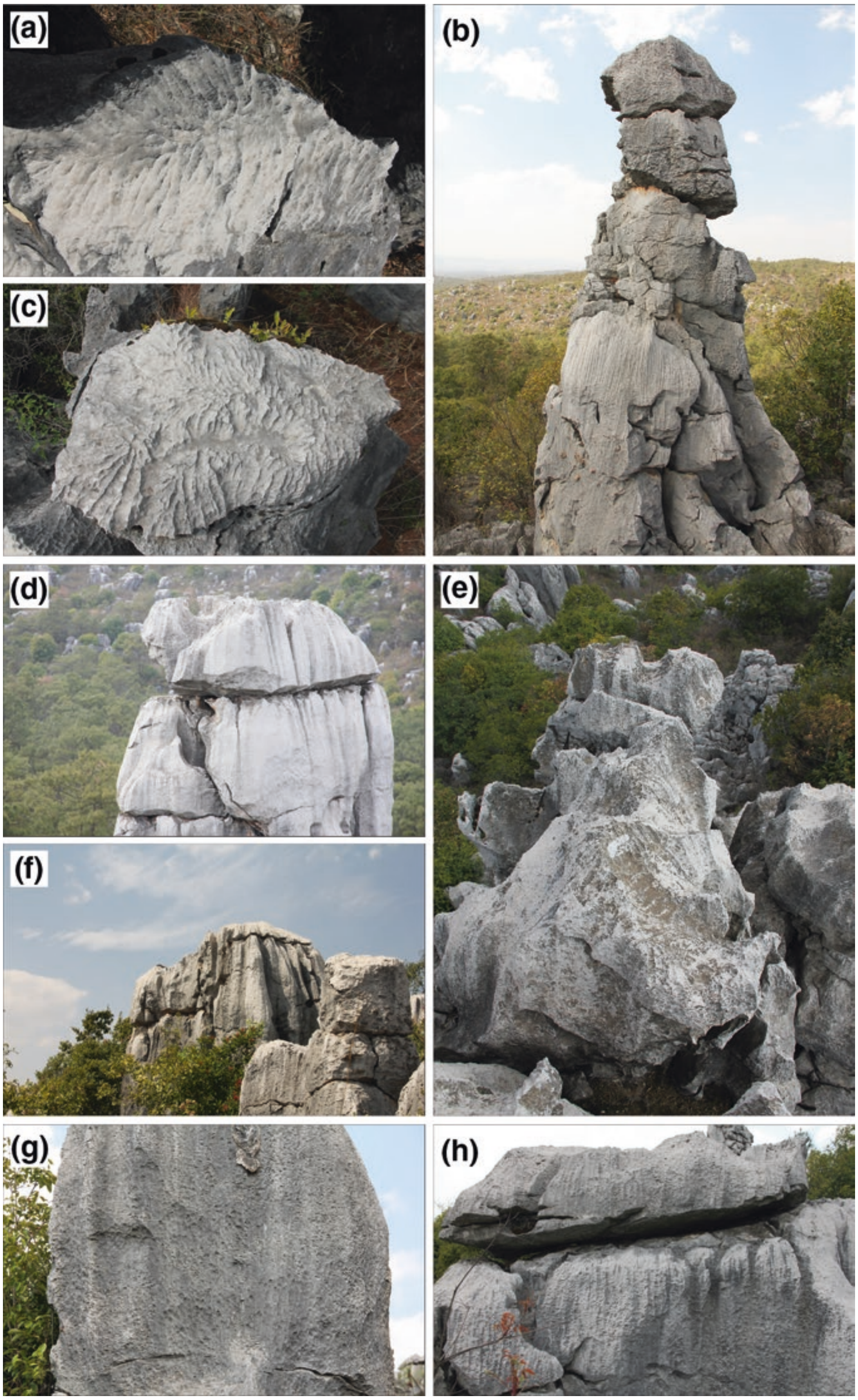
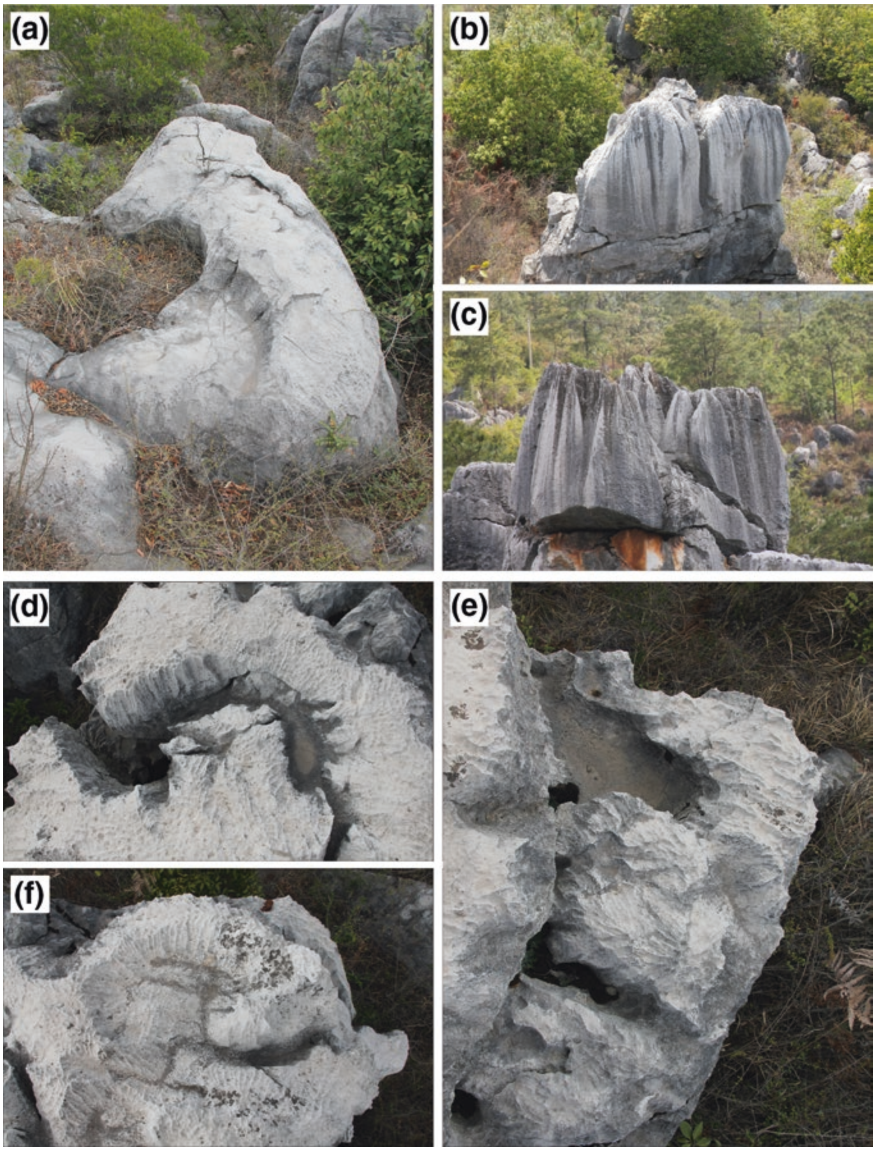


Fig. 1.10 Rock forms carved by rain and creeping water: **a** rain flutes, **b** rain flutes on the wall, **c** rain flutes and channels between them, **d** wall channels, **e** funnel-like notch with rain flutes, **f** wall channels, **g** rain scallops, and **h** reshaped bedding-plane anastomosis with wall channels

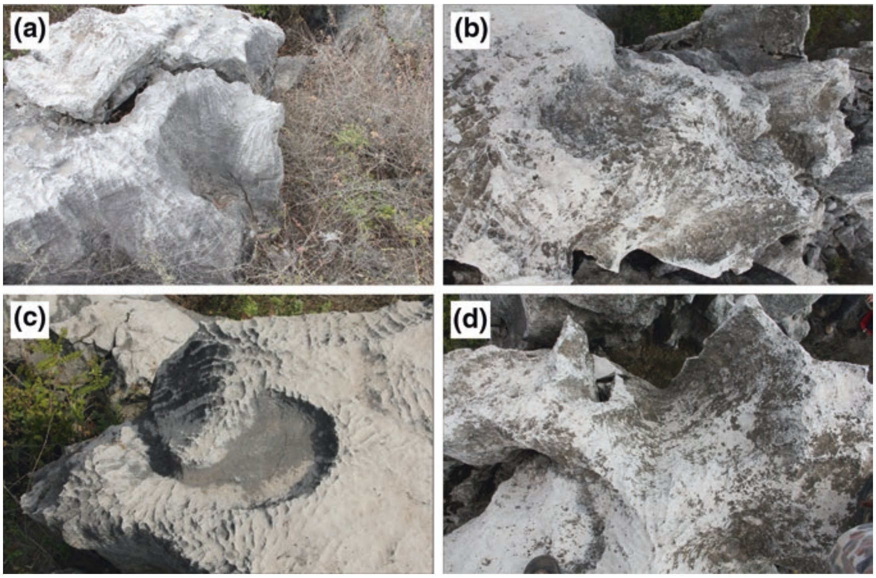
moses usually have elliptical cross-sections or develop paragenetically upward; after the denudation of the rock, they were first reshaped below the soil or moss covering their bottoms. Water flows along the bottoms of denuded cavities. In some cases, the lower section of the cavity has become completely predominant.



◘ **Fig. 1.11** With rain reshaped subsoil rock forms: **a** subsoil notch with rain flutes, **b** funnel-like notch reshaped by rain, **c** by rain reshaping top of the pillar, **d** subsoil channel reshaping by rain, **e** subsoil cup reshaping by rain, and **f** from subsoil cup to solution pan toward funnel-like notch

1.4.4 Developmental Diversity of Rock Form Shaping

To understand the formation and transformation of rock forms, it is necessary to pay attention to developmental diversity. This can be seen in the example of the formation of funnel-like notches. These can be wide open and shallow or half, three-quarters, or almost closed funnels of various diameters ranging from a few centimeters to several meters. Common to all of them is the collection of water at the top of the rock or at its edge. Funnel-like notches are of completely subsoil origin as the mouths of subsoil channels (◘Fig. 1.12a). A subsoil origin is also typical of those at the foot of pillars where wall channels lead to gently sloping rock covered with soil. They also form at bends on the tops or at the ends of subsoil channels dissecting the top and from channels collecting water from rain flutes from where water flows down the wall. They can form at the end of both networks. Water creeping evenly over surfaces also merges in funnel-like notches at bends (Slabe 2005). They also form from subsoil cups at the edges of tops (◘Figs. 1.12b and 1.10c) and are found at the outer edge of interbed



◘ **Fig. 1.12** Developing model: **a** from subsoil to rain funnel-like notch, **b** subsoil notches and channels are reshaping by rain on the top of the ridge, **c** solution pan reshaping by rain, and **d** subsoil funnel-like notch reshaping by rain

anastomoses where water flows down walls whether the water flows from one cavity, which of course is wider, or from numerous cavities of a wide system. Wide notches, which can be of subsoil origin, can be dissected by narrower notches.

They often have a subsoil cup on their floor that spreads downward as the rock dissolves. This can develop into a solution pan that over time usually wedges out. It first opens at the edges and becomes a horseshoe-shaped depression that eventually grows into a channel (◘Fig. 1.11f). Funnel-like notches can grow into wide channels or continue to expand downward with a narrow channel (◘Fig. 1.12d). On walls dissected by steps, they can cascade one below another and be connected. As water trickles and creeps down them, they become deeper and, along subsoil cups and solution pans, wider as well; where rainwater reaches them directly, they widen evenly and are dissected by flutes.

◘ **Fig. 1.13** Notches formed under vegetation

1.4.5 Rock Under Vegetation

On rock that was covered by vegetation, usually creepers or dense scrubs, there are oblong small notches about 1 cm in diameter. These can measure several decimeters in length and be connected in networks (Fig. 1.13). They cover tops and large surfaces or just belts on walls. Biocorrosion is also active below lichen covering the rock in thin layers and is particularly distinct in cavities. It primarily influences the fine dissection of the rock.

1.5 Conclusion

All the carbonate beds in the stone forest have a homogeneous and monotonous composition. They are composed of biogenic and non-biogenic carbonate grains of uniform sizes and contain the same amount of total carbonate. Carbonate grains connected by micrite to microsparite occupy between 90 and 95 % of the rock of the wackestone to grainstone type. All the beds studied show similar karstification, and the properties of the rock enable the formation of even fine rock forms.

The denuded stone pillars acquire sharp forms. The rounded subsoil surfaces of stone teeth and the mostly larger rock forms on them have been transformed by rainwater and water creeping down the rock as well as by water percolating through it. This water finely dissects the rock and sharpens the edges. Before the rock was completely denuded, the soil covered only parts of it and in places dictated the formation of an intermediate rock relief.

The stone forest and its rock relief have been distinctly transformed primarily in the areas of larger stone pillars located higher on the rounded peaks and the ridges between them. The formation characteristics of the uncovered subsoil rock forms are the traces of the relatively rapid and recent denudation of this part of the stone forest. Subsoil rock relief dominates in the stone forest and on the stone teeth on the slopes where the pillars are shorter as a rule.

The described stone forest is a typical example of development from subsoil karren that dissected the tops and slopes of rounded hills. The influence of the dissected karst surface and its position on an elevation on the development is emphasized. Although other stone forests also develop from subsoil karren, their position on dissected surfaces and the level of the groundwater dictate different formation characteristics. An extreme example of diversity is provided by the stone forest in the Xian Nu Hu basin which is periodically flooded. This flooding is clearly visible in the rock relief of stone pillars. A comparison is in preparation of these types of impacts as well as of rock composition and rock fissuring characteristics (Knez et al. 2011) on the development of Shilin, which is a rich source of knowledge about the development of a karst surface during gradual exposure from under sediment and soil. The long-term formation of stone forests reveals numerous stages of development that are fundamental for comparison with other karst regions. The construction of the motorway on the low karst of southern Slovenia revealed initial stages of the development of this type of stone forest (Knez et al. 2004, 2016; Knez and Slabe 2006b, 2007b; Culver et al. 2012). And last but not least, subsoil formation and the subsequent denudation of karren is one of the most frequent patterns for the formation of karst surfaces.

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